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Measurement of Nuclear Dependence in Inclusive Antineutrino Scattering with MINERνA

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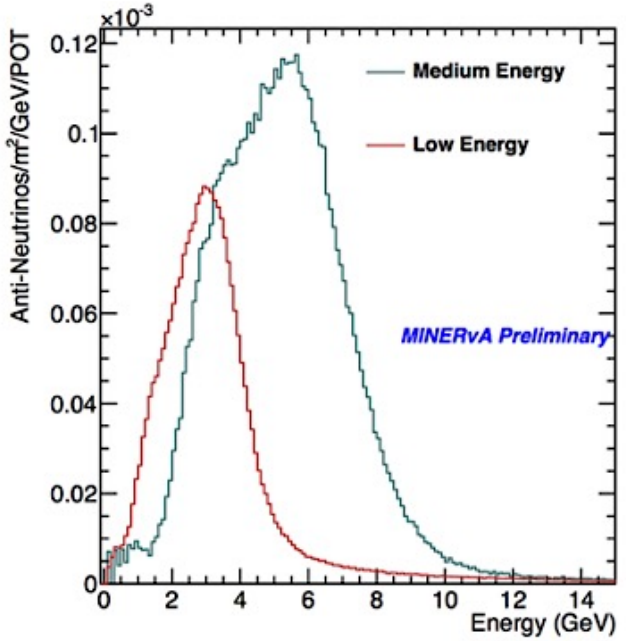
MINERνA

- High statistics, self-contained precision studies of ν-A scattering
- 5 different nuclei: He, Pb, Fe, C, H_2O
- Active region: segmented solid scintillator (CH)
- MINOS spectrometer: muon momentum and charge
- NUMI beamline at Fermilab



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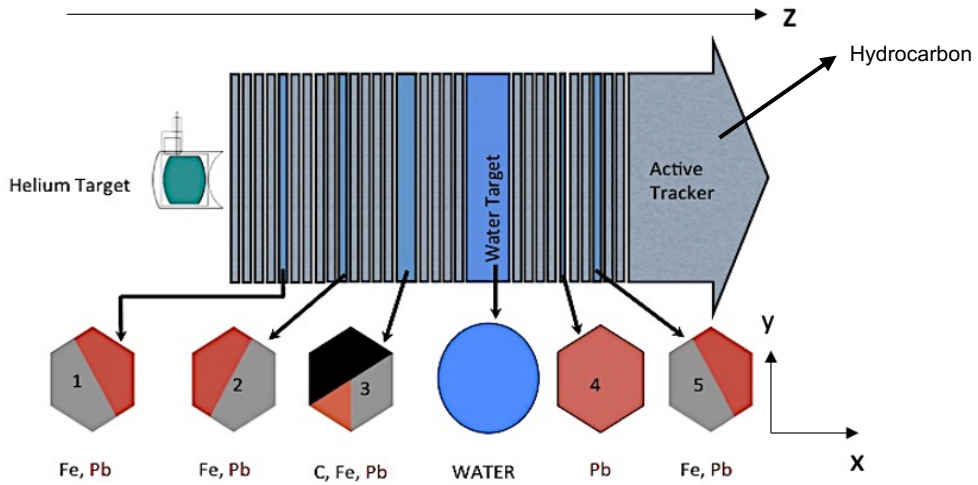
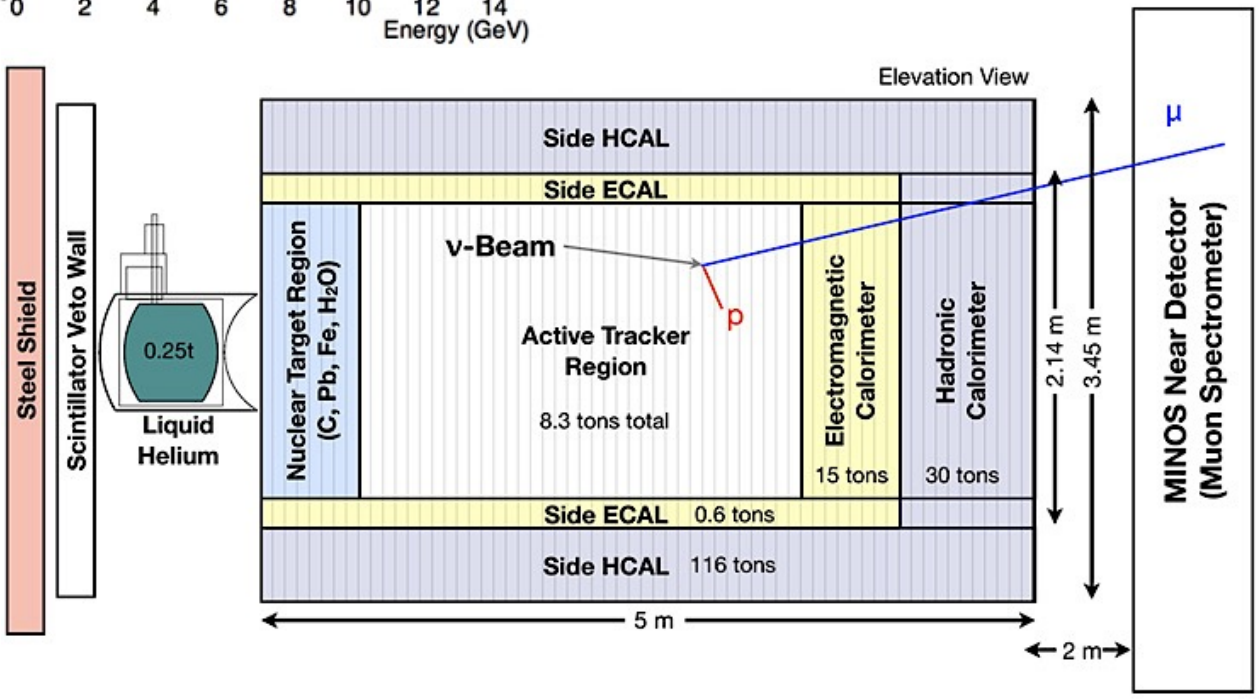
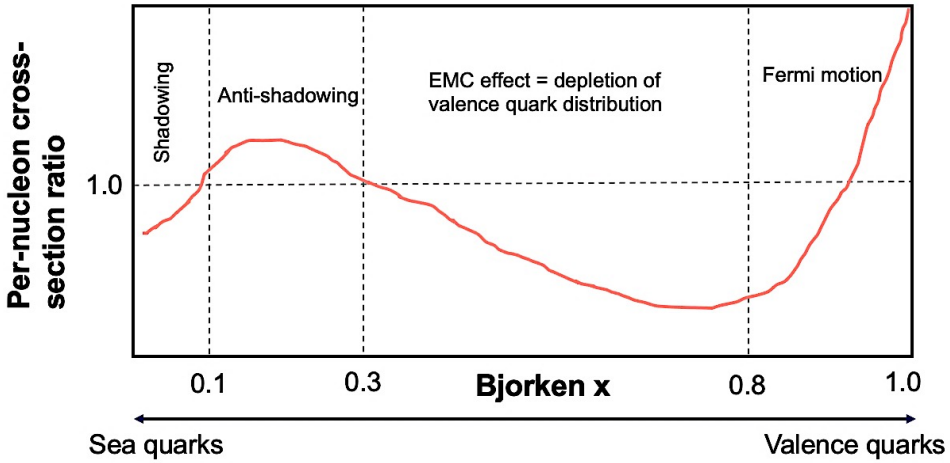
Regime \ Mode	ν (POT)	$\bar{\nu}$ (POT)
Low (LE) ~ 3.5 GeV	4×10^{20}	1.7×10^{20}
Medium (ME) ~ 6 GeV	12.1×10^{20}	12.4×10^{20}



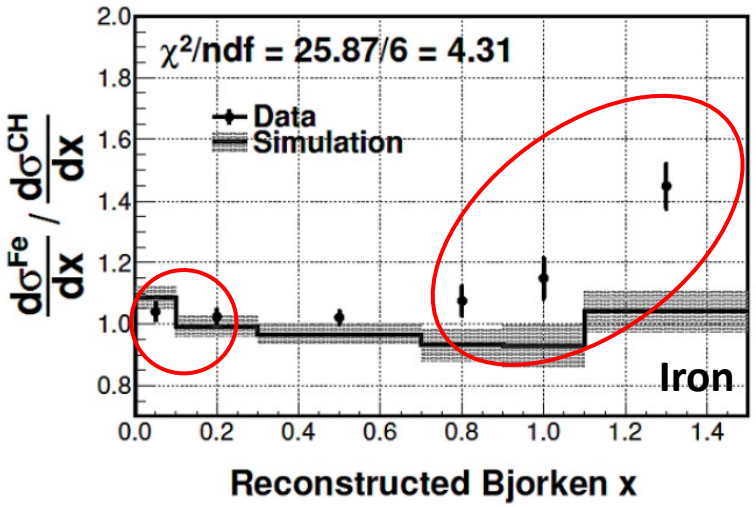


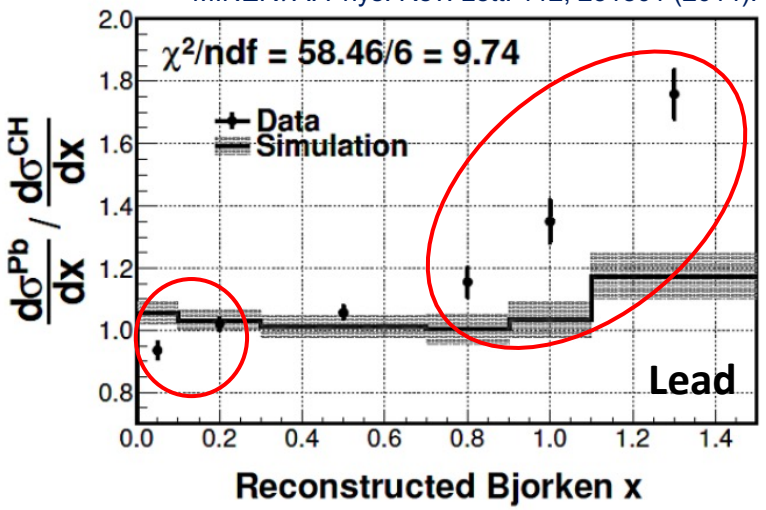
Nuclear Modifications



- Nucleons bound in a nucleus by the strong force – requires modifications compared to a free nucleon
- Modifications classified in terms of Bjorken x
  - Fraction of the nucleon's momentum carried away by the struck quark

MINERνA. Phys. Rev. Lett. 112, 231801 (2014).





- **MINERνA low energy result:** inclusive neutrino nuclear target to scintillator cross-section ratio
- Fe 19 024 events, Pb 23 697 events

1D Inclusive $\bar{\nu}_\mu$ Cross-section

- Measure cross-section of $\bar{\nu}_\mu + A \rightarrow \mu^+ + X$ in Fe, Pb, and C, and extract differential cross-section ratio of nuclear target to scintillator

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\Sigma_j U_{\alpha j}(N_{data,j} - N^{bkg}_{data,j})}{\epsilon_\alpha \Phi T(\Delta x)}$$

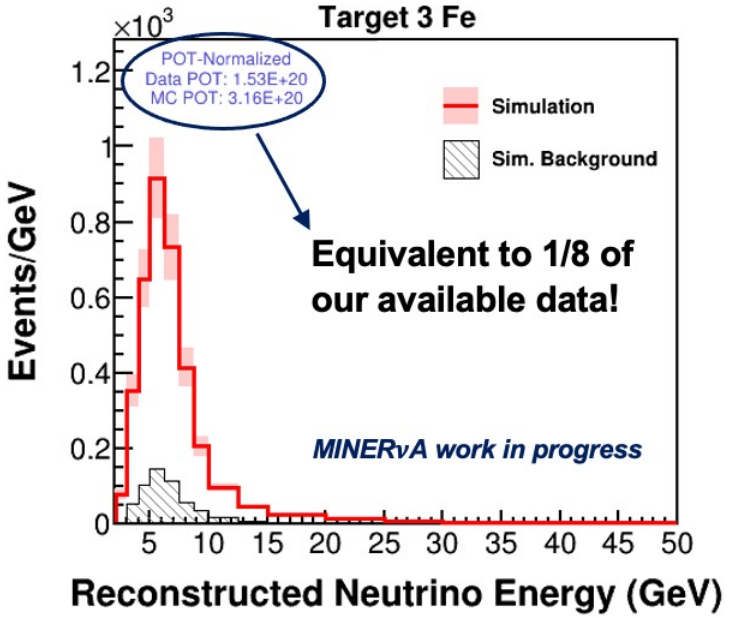
- **Variables of interest:** neutrino energy E_ν, Bjorken x

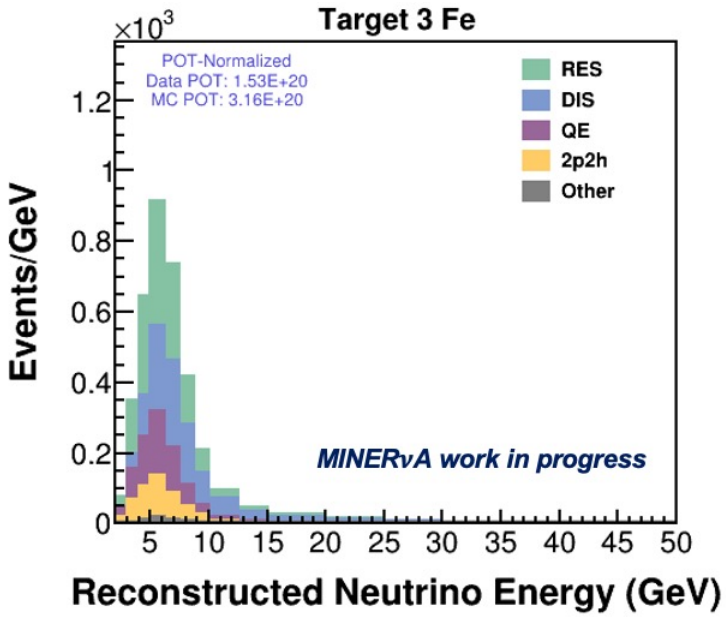
$$E_\nu = E_\mu + E_{had}$$

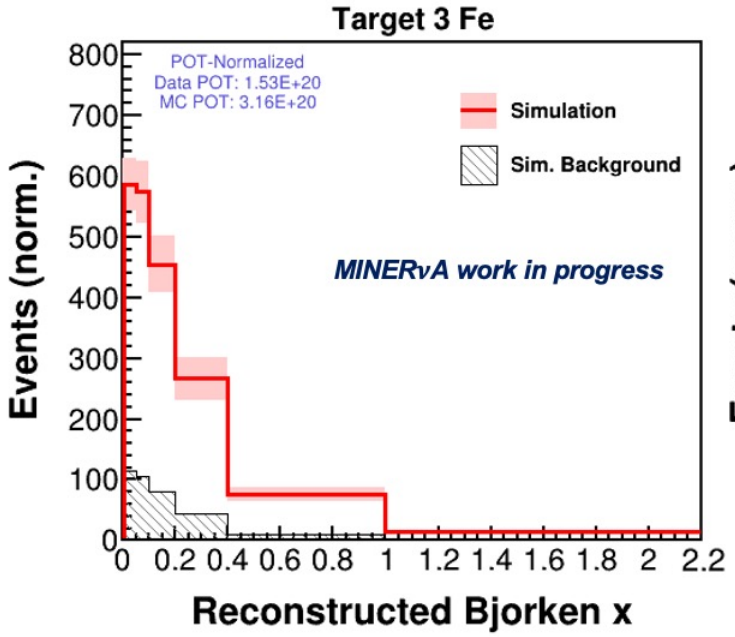
$$x = \frac{Q^2}{2(E_\nu - E_\mu)m_N}$$

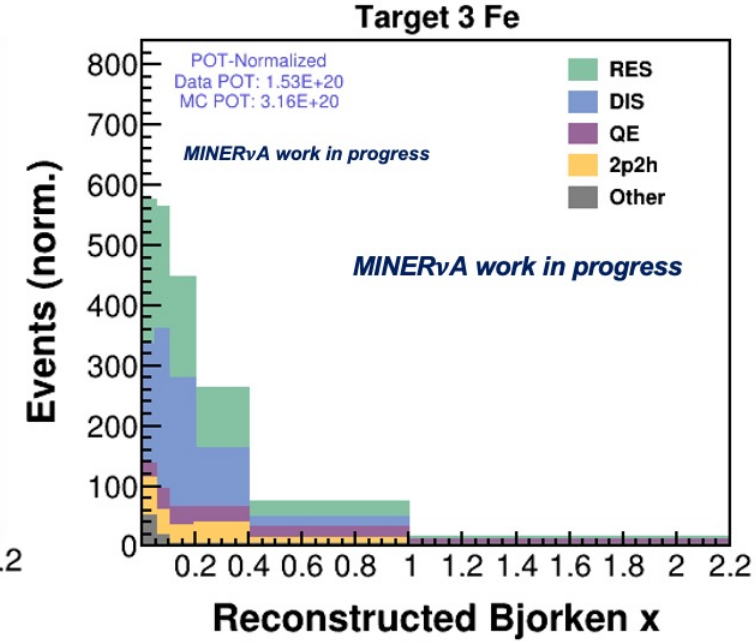
$$E_\mu = \sqrt{m_\mu^2 + p_\mu^2}$$

$$Q^2 = 4E_\mu E_\nu \sin^2(\theta_\mu/2) - m_\mu^2$$





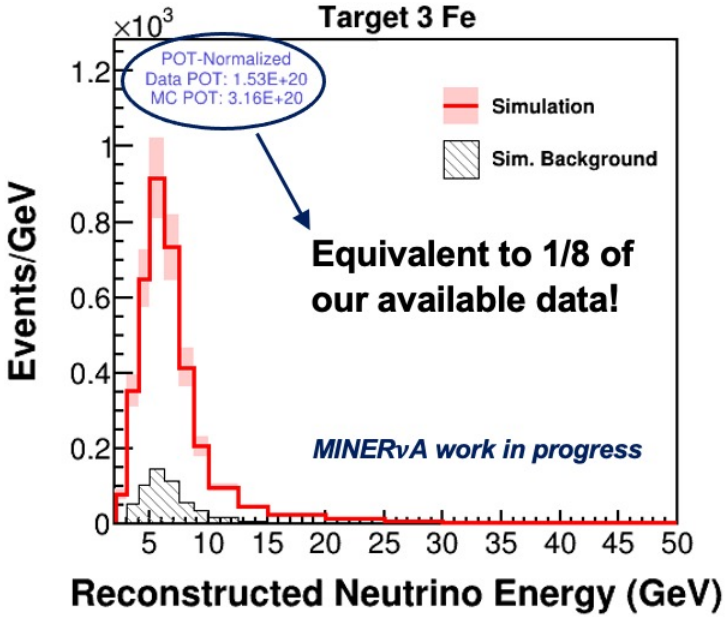


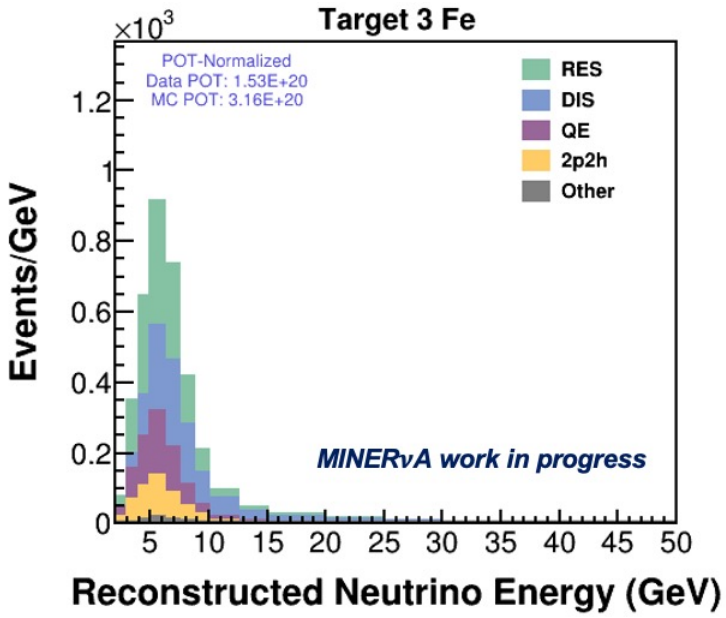


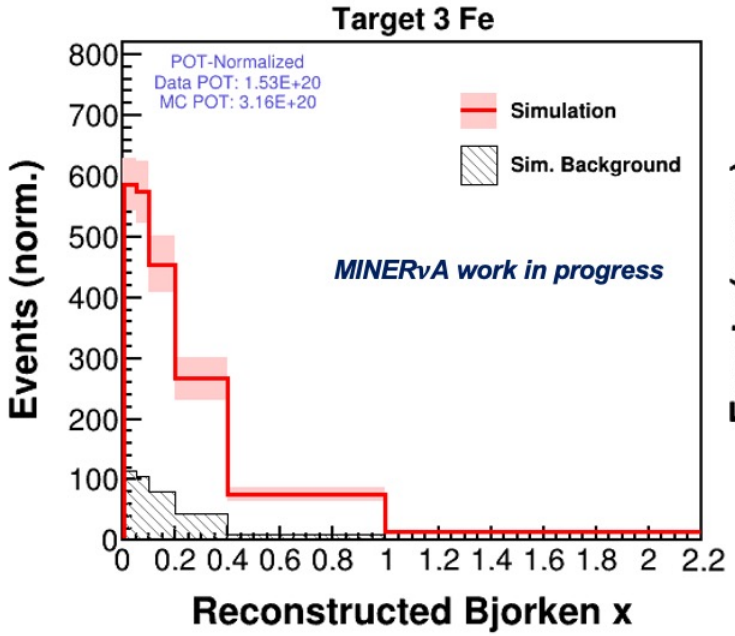
1D Inclusive $\bar{\nu}_\mu$ Cross-section

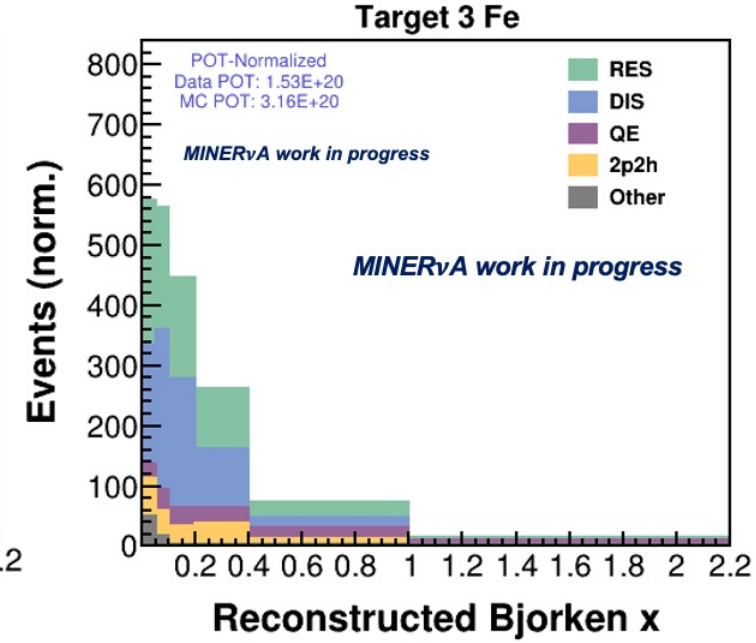
- **Signal definition:** Charged-current $\bar{\nu}_\mu$ in given target and material, with muon $2\ \mathrm{GeV} \leq E_\mu < 50\ \mathrm{GeV}$ (and $\theta_\mu \leq 17°$)
- GENIE 2.12.6 with MINERνA modifications
- Flux constraint using neutrino-electron scattering
- Vertex reconstructed using machine learning (ML) – deep convolutional neural net

Estimated number of events in Fe including all ME antineutrino runs $\approx 2.5 \cdot 10^5$



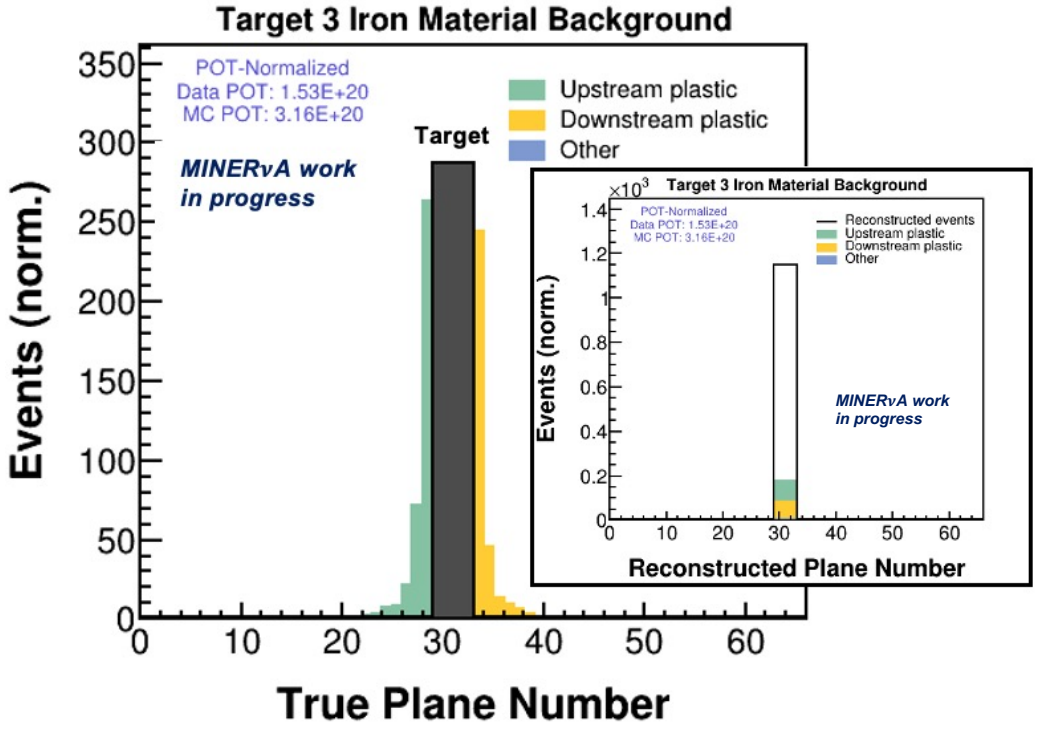


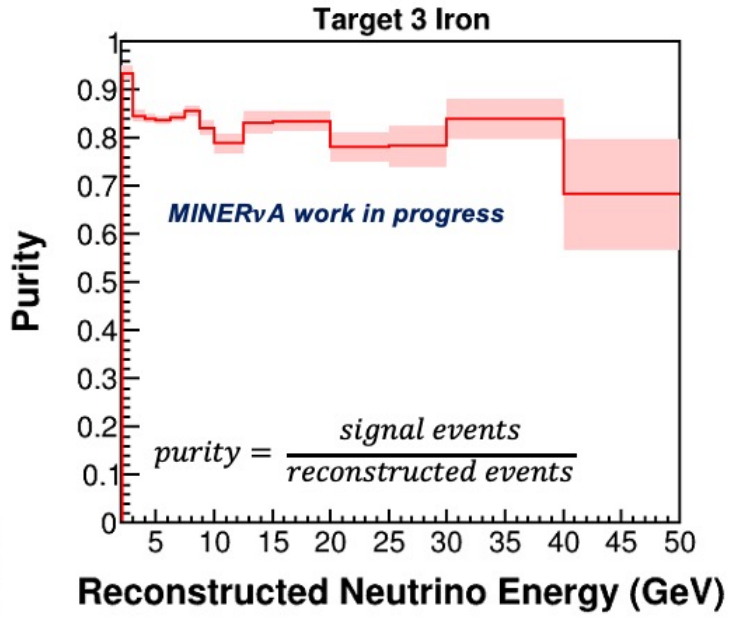


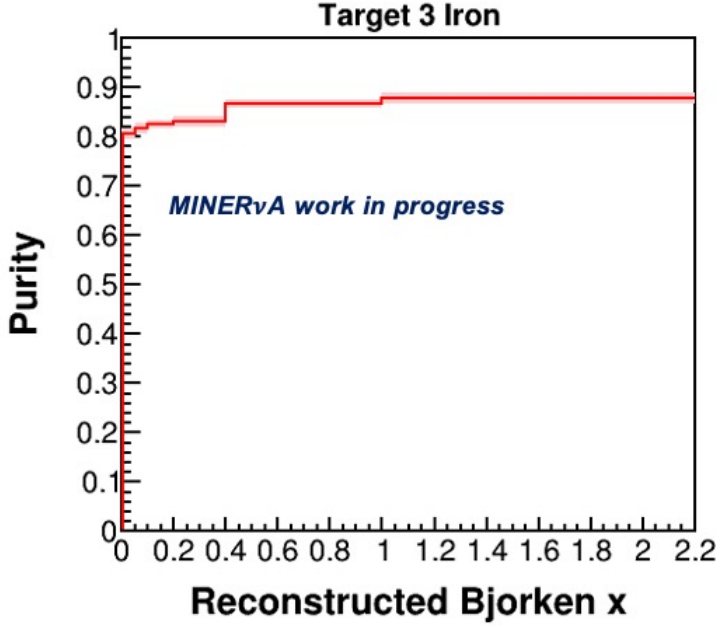


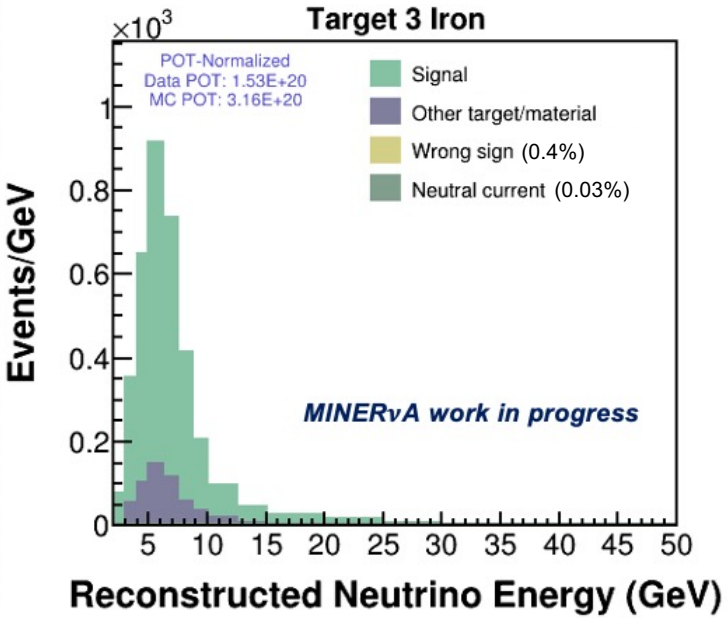
Backgrounds

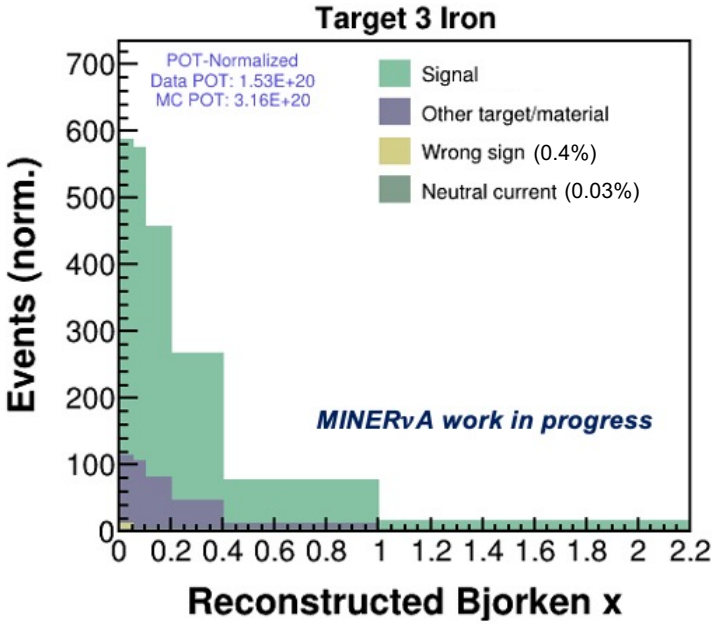
- High purity selection (~ 84%)
- **Main background in targets:** events reconstructed in the target that truly originated in the scintillator (= plastic)





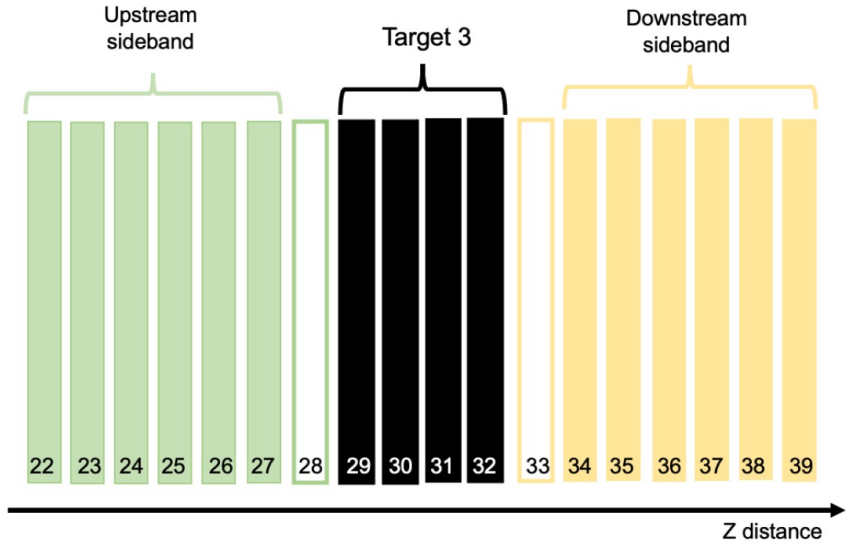




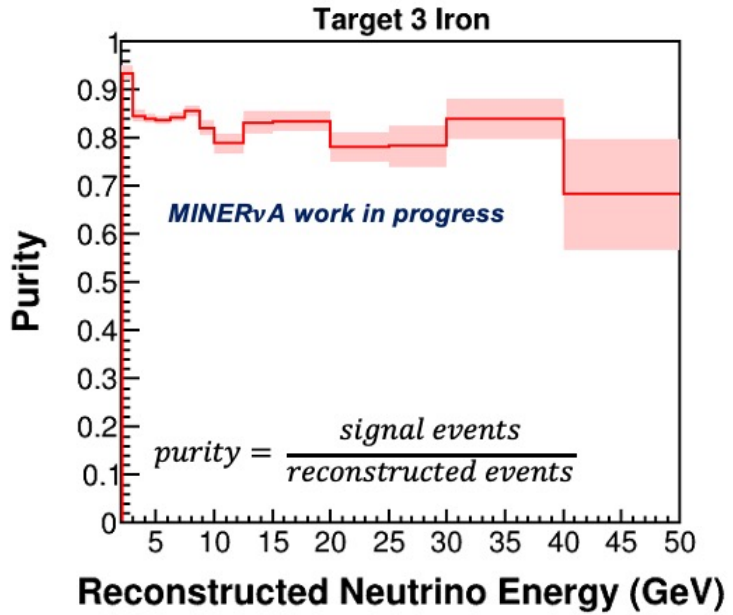


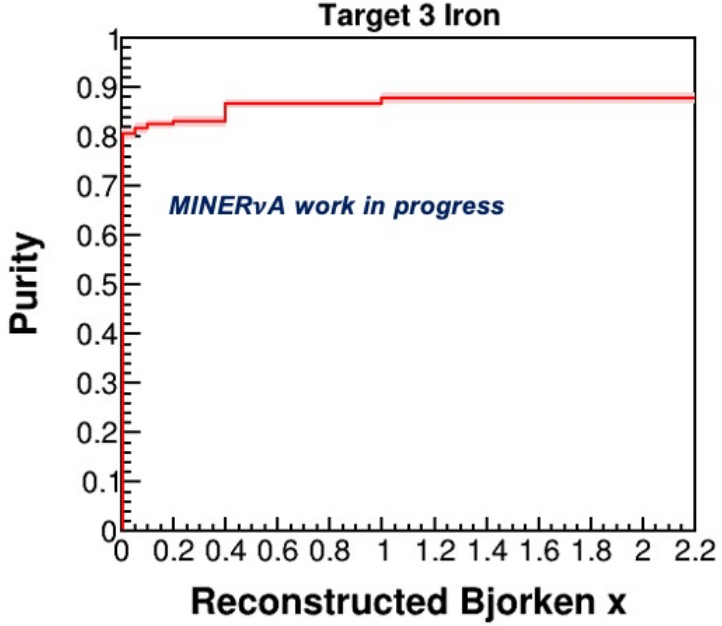
Backgrounds

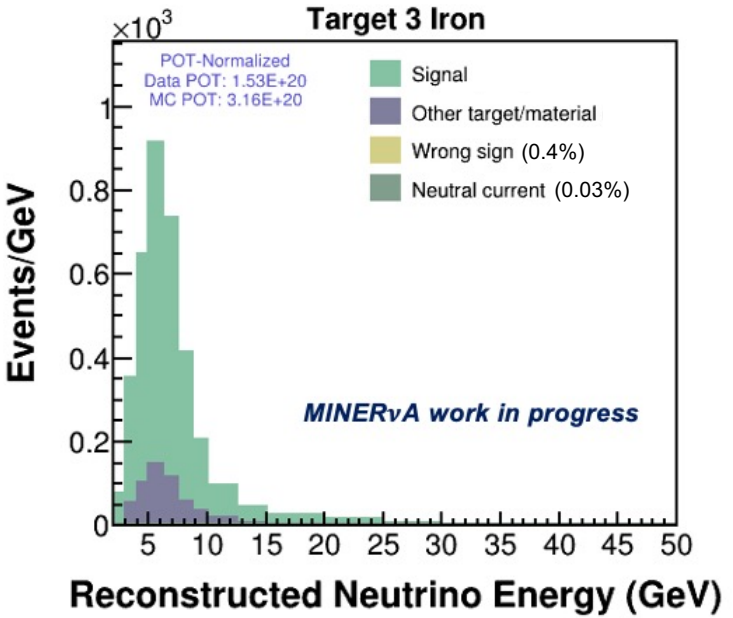
- High purity selection (~ 84%)
- **Main background in targets:** events reconstructed in the target that truly originated in the scintillator (= plastic)
- Upstream and downstream sideband plastic constraint to data

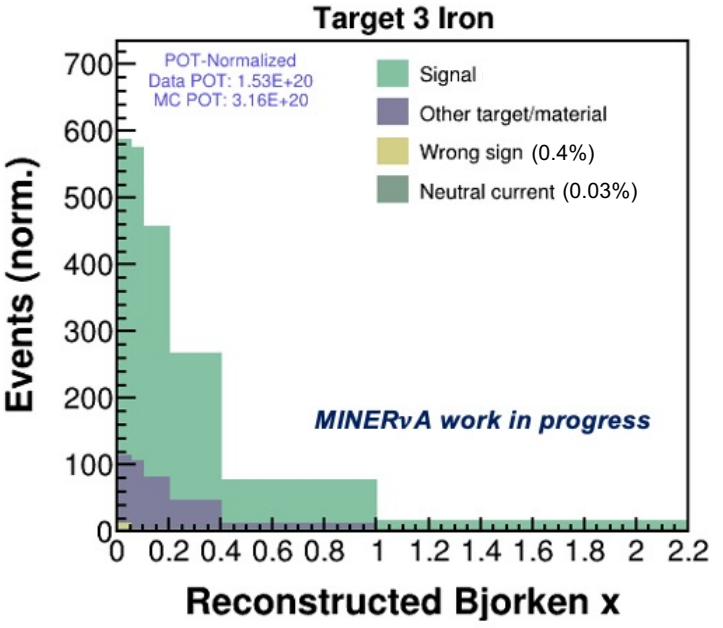


- **Main background in the scintillator**: neutral current and wrong sign events









Migration & High Bjorken x region

Why x > 1.0 region?

- Estimated events in Fe in 1.0 < x < 2.2 bin $\approx 2.5 \cdot 10^4$
- Nucleons in nuclei: wave-functions can overlap → short range nucleon-nucleon correlations (SRC)
- Theoretical predictions that at $p > p_F$: SRC dominant
- From electron scattering data: 2-nucleon SRC plateau at $x > 1.5$
- Scattering from nucleons in SRC: data on the modification of deeply bound nucleons

- Detector resolution and reconstruction → smearing
- Unfolding to true distribution: introduces model bias and/or statistical fluctuations

Conclusions & Next Steps

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- MINERνA: cross-section measurements and measurements of nuclear modifications
- ME data in targets are being analysed!
- Important handle to probe and understand nuclear effects

1D Inclusive $\bar{\nu}_\mu$ Cross-section Measurement (E_ν, x)

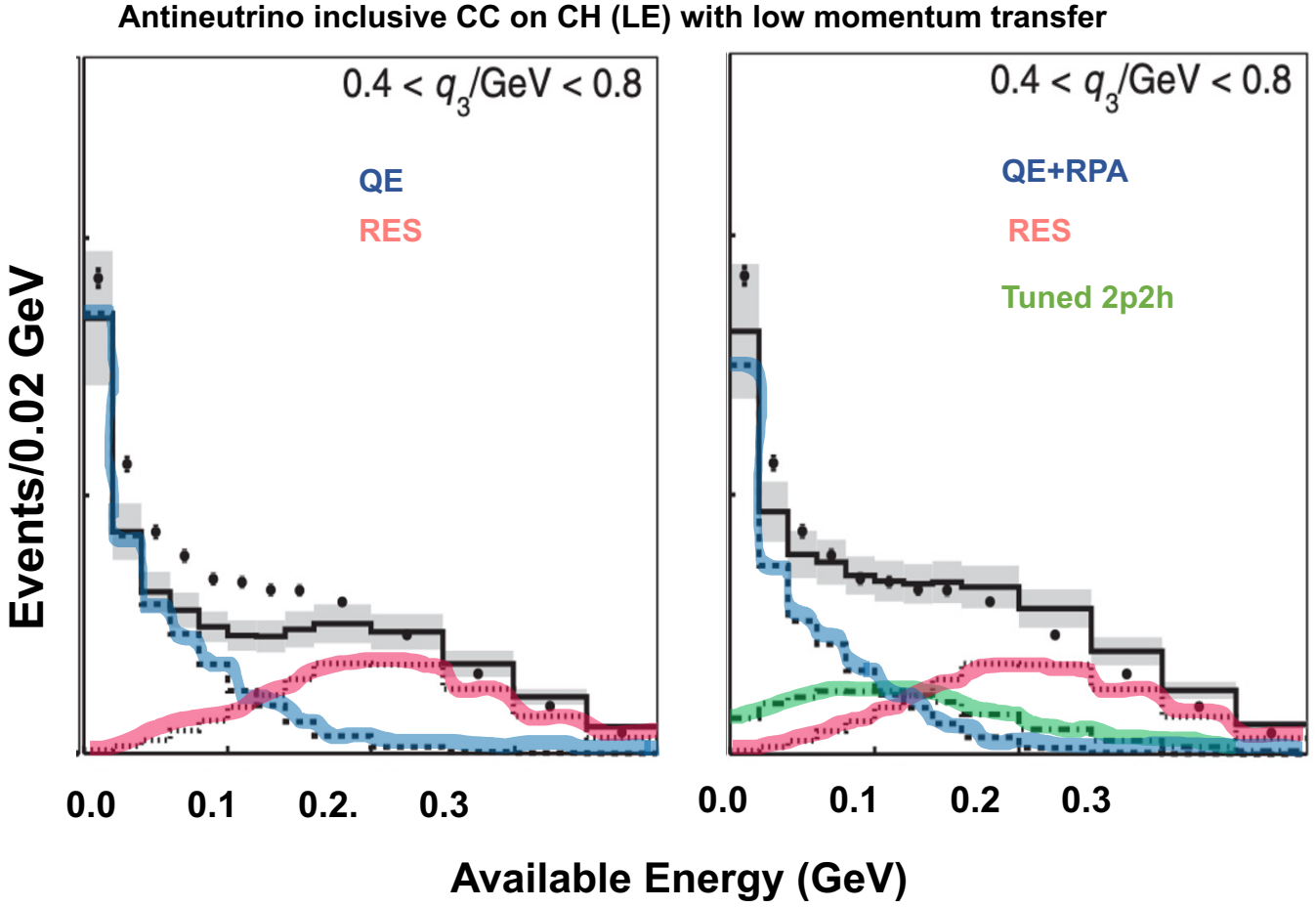
- Include the rest of ME antineutrino runs + unfolding → extract cross-section
- High Bjorken x region: modify GENIE predictions/account for lack of modelling in $x > 1.0$
- Perform equivalent analysis for the scintillator in the tracker to report ratios

BACK-UP

Model Information

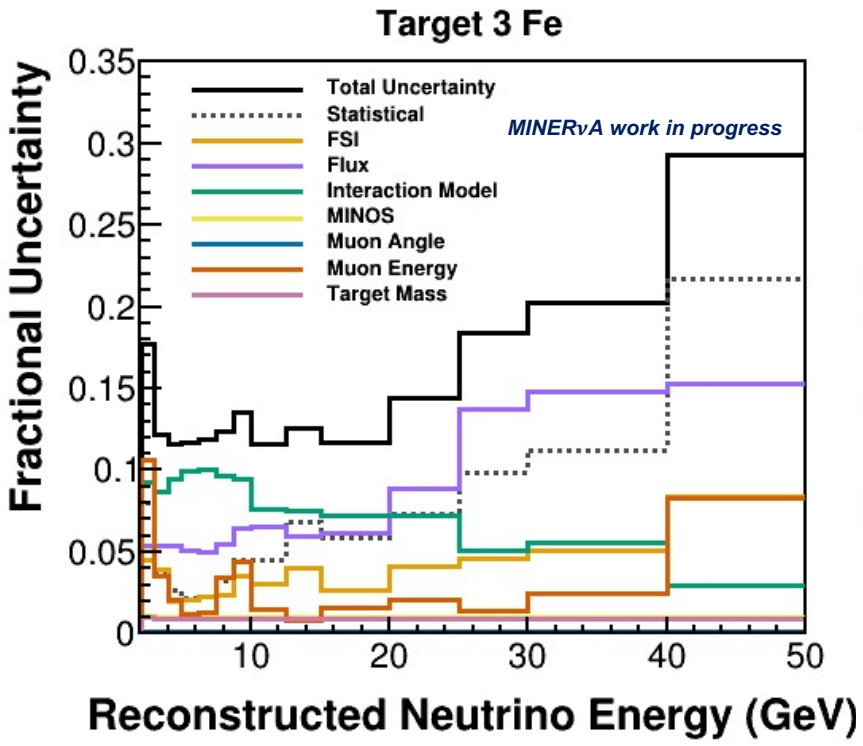
- GENIE version 2.12.6
- RPA suppression to better simulate CCQE:
  arXiv:1705.02932 (2017) [hep-ex]
- Reduced non-resonant pion production:
  Eur. Phys. J. C76, 376 474 (2016)
  - Decreased non-resonant pion production by 43%
- Added + enhanced Valencia 2p2h:
  Phys. Rev. Lett. 116, 071802 (2016)
  - Integrated over all phase space, the rate of 2p2h is increased by 50% over the nominal prediction

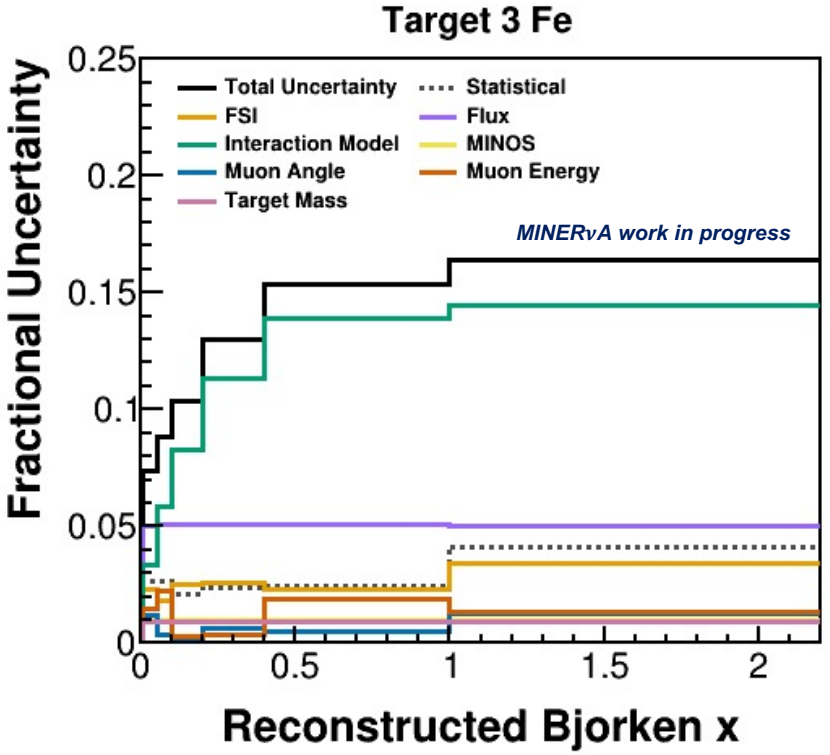
Modified from Phys. Rev. Lett., 120, 221805 (2018)



Systematic Uncertainties

- Evaluated by re-extracting the event rate/cross-section using modified simulations
  - Size of each related to the uncertainty in each source
  - Multidimensional histogram container class @MinervaExpt on GitHub
- **Largest systematic:** interaction model and flux
  - Flux constrained using neutrino-electron scattering (uncertainty reduced from 7.6% to 3.9% for ν mode)
  - New flux constraint coming up!
- Missing systematics: hadronic energy, ML vertex
- Currently driven by statistical uncertainty (one ME run)



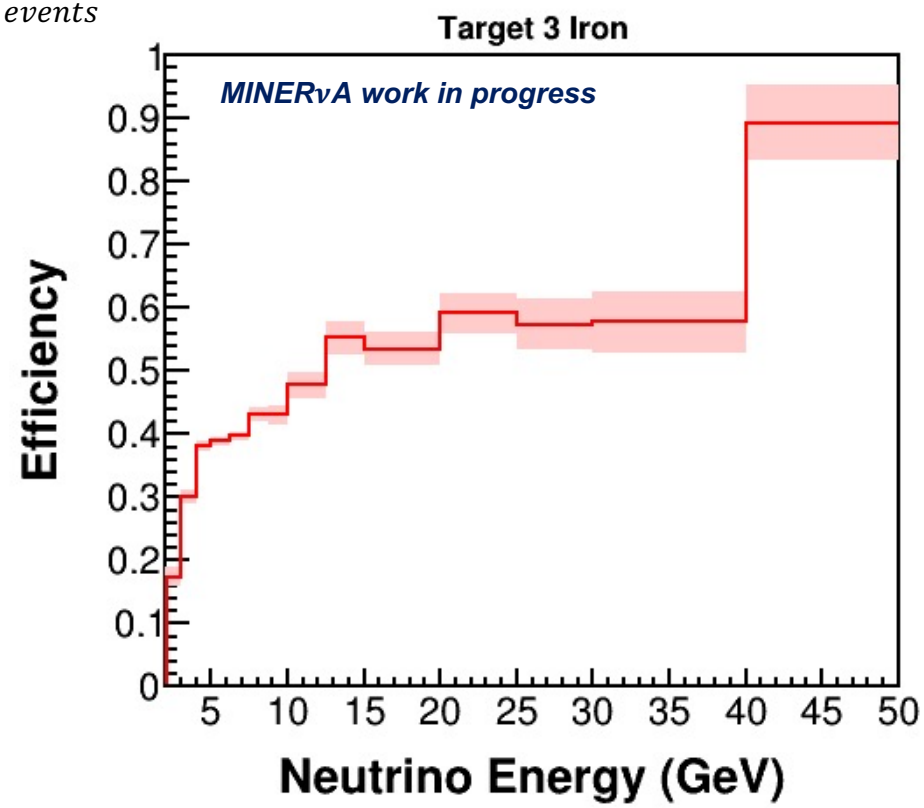


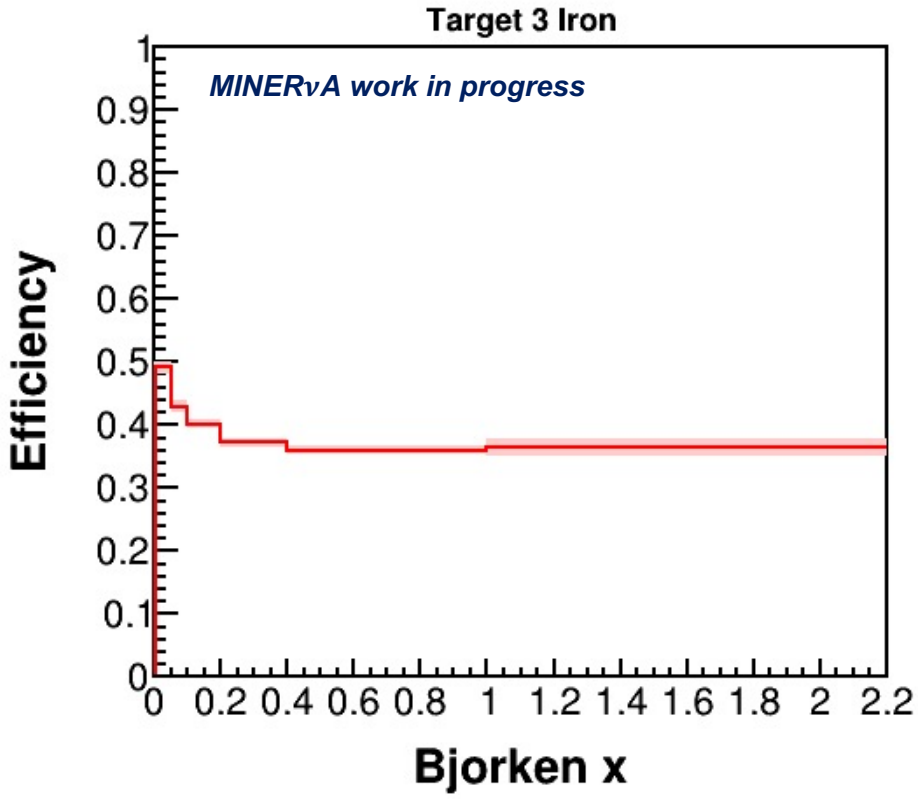
Fractional Uncertainty on Number of Events (Simulation)

Efficiency/Acceptance Correction

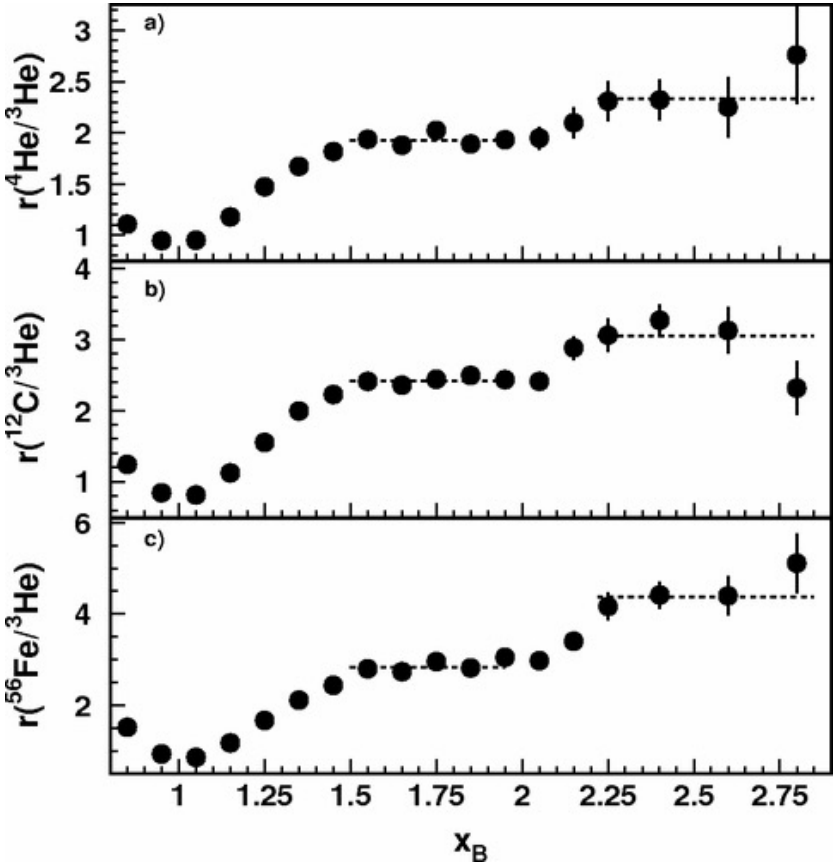
- Lowered by requiring MINOS matched events
- Allow for out of fiducial volume and $\theta_\mu > 17°$ events to migrate in and out → efficiency/acceptance corrected

$$efficiency = \frac{selected\ signal\ events}{total\ signal\ events}$$





SRC, Initial Nucleon Momentum



CLAS Collaboration. Phys. Rev. Lett. **96**, 082501 (2006)